

A COMPREHENSIVE METHOD AND FOCUSED ON POWER QUALITY INDEXES AND EFFICIENCY FOR THE DESIGN OF MICROGRIDS WITH MULTIPLE DGUS

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ABSTRACT

This paper presents a comprehensive method, focused on power-quality indexes and efficiency for the design of microgrids with multiple DGUs interconnected to the ac grid through three-phase multi-Megawatt medium-voltage pulse width-modulated-voltage-source inverters (PWM-VSI). The proposed design method is based on a least square solution using the harmonic domain modeling approach to effectively consider explicitly the harmonic characteristics of the DGUs and their direct and cross-coupling interaction with the grid, loads, and the other DGUs. Extensive simulations and analyses against PSCAD are presented in order to show the outstanding performance of the proposed design approach.

Index Terms : Harmonic analysis, design optimization, power quality, PWM-VSI

INTRODUCTION

Ideal operating conditions are increasingly difficult to sustain as valid, since harmonic generation, interaction of controls and harmonic components, resonances, harmonic stability issues, etc, are phenomena commonly reported in systems with high harmonic penetration [7]. In practical networks with power electronic-based DGUs, this could lead to erroneous or unfavorable operating scenarios. This gap has been recognized and addressed in the open literature, although not in a holistic way. For instance, [8] deals with the power transfer capability problem of DGUs

including harmonic distortion, and considering power quality regulations at a specific point of the network. Reference brings out some pitfalls of electric power-quality indexes allowed by international regulations showing that being within the limits is not enough in order to ensure proper performance of the DGUs electrically close to each other. In more sophisticated approaches, the power quality on the distribution system is improved by the use of harmonic compensation methods in the control schemes of the interconnected DGUs.

In this way, one of the best practice to mitigate the adverse harmonic effects is the proper design of the passive filters connected to the end terminals of power electronic converters.

Several design methods or procedures, specially for the LCL filter, have been proposed. However, most are based on a trial and error process in which their difficulty and convergence problems considerably increase for systems with multiple DGUs based on power electronic converters, specifically from medium to high power levels. This paper proposes a comprehensive approach, based on optimization and the extended harmonic

domain (EHD) [21], for the design of multiple grid-connected multi-Megawatt medium voltage PWM-VSI with LCL filters. This is carried out by means of a Nonlinear Least Squares formulation (NLSQ), which calculates the filter parameters and the steady state control variables which meet certain proposed reference operating conditions and includes power-quality restrictions and efficiency. As an example, the design of two DGUs, based on three-phase PWM-VSIs, which are connected to a microgrid is presented. Two case studies are presented to show the proposed design approach, one considering that the interconnections grid is unknown and the other when it is known. The obtained results show the remarkable good performance of the proposed design approach on both cases, along with advantages over other design methodologies, which rely on the comprehensive consideration of multiple design objectives.

II. DESIGN OF DGUS

Three main elements could be identified in the design of a DGU. (1) The Design Objectives (DO) (power quality, operating conditions, size limitations, cost, etc.), (2) the External Conditions (EC) (distributed resource, grid equivalent, weather events, faults, generation outages, etc.) and (3) the Designable Elements (DE) (topology, component values, control parameters, etc.). In this context, a proper design can be summarized as the selection of certain DE that ensure the fulfillment of the DO in the presence of some EC. This requires to understand in detail the relationships and interactions among these main elements.

Fig. 1 shows a very basic representation of a typical DGU and some of the above identified main elements are shown (DO, EC and DE). From Fig. 1 the DO could be established, for example: DC bus voltage, DC voltage ripple, RMS voltage at *PCC*, active power at *PCC*, reactive power at *PCC*, THD voltage at *PCC*, current ripple at *PCC*, among others. Some of the DE are: distributed resource topology, power electronic topology, AC and DC filter topologies, control unit topology, switching frequency, power switches ratings, DC filter component values and AC filter component values, control unit gains, among others. In order to have a selection of the DE that ensures that the reference design objectives (DO_{ref}) are met under bounded variation of certain EC, it is then required to understand the relationships between these main elements.

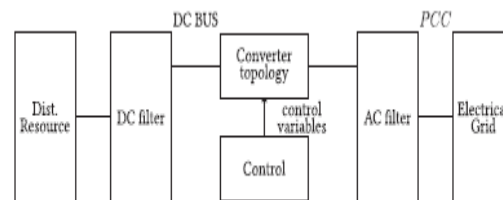


Fig. 1. Simplified layout for design.

It is clear that the relationships between the DO and the DE are far from linear and decoupled. Fig. 2 shows schematically an insight of the intricate relationships among the DO, DE and EC; depicted by grey circles, blue ovals and green squares, respectively. The pointing arrows between these elements are links with the elements that have influence on or relation to the

final value of them. Solid and dashed lines represent strong and weak interactions, respectively.

Fig. 2 shows an insight of the challenges in the designing of DGUs. Some of the most common practices used to tackle them are:

(1) settle many of the designable elements based on

experience and a priori knowledge, especially those in respect the topology, (2) decouple the relationships by considering only the most relevant designable elements for each design objective, (3) neglect some design objectives focusing only on the most important.

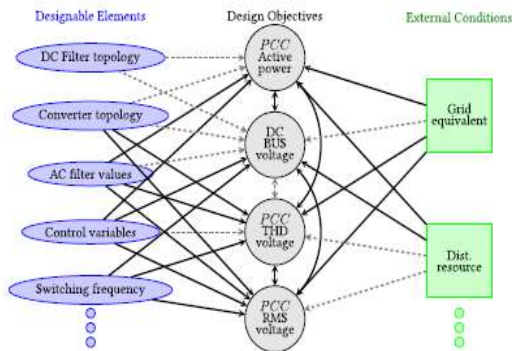


Fig. 2. Relationship between designable elements (DE), design objectives (DO) and external conditions (EC).

III. DISTRIBUTED GENERATION UNIT SUBSYSTEM MODEL

Fig. 3 shows the topology for DG_n subsystem with $n = \{1, 2\}$. The time-domain three-phase variables are denoted by lowercase bold letters that in general represent vectors of size (3×1) constructed with the phases a, b and c , i.e., $\mathbf{i}_{n1} = [i_{n1a}, i_{n1b}, i_{n1c}]^T$; T_n is the $Y - \Delta$ transformer with parameters r_{tn} , l_{tn} and a_n referred to the primary winding; control variables m_n and θ_n are the modulation index and phase

shift, respectively, of the modulating signal from which the PWM block generates the switching functions. For a closed-loop operation, the control variables will be generated by a control strategy for given reference operating conditions.

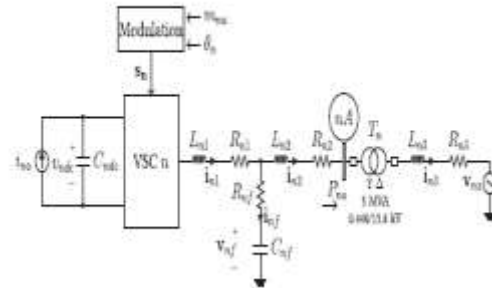


Fig. 3. Distribution generation unit of test system.

III. DESIGN ELEMENTS OF PROPOSED SYSTEM

1) **Steady State Control Variables m_n and θ_n** : By considering the control variables as DE, the closed-loop performance of each DGU is considered in the design. In this way, the control references can be included as DO, allowing to consider the nominal operating conditions in the design.

2) **Input dc Current Source i_{no} and dc Side Capacitor C_{ndc}** : By designing these parameters, the power quality of the dc voltage bus along with power rating related to the operating conditions (such efficiency and transferred power) are able to be introduced as DO.

3) **LCL Filter Passive Components L_{n1} , L_{n2} , R_{nf} and C_{nf}** : The LCL filter parameter are mainly related with the power quality of ac signals. However, their design impacts not only

power-quality DO but also on the overall closed-loop performance of the DGU. One example is to increase the damping resistance R_f in order to reduce the resonance peak, however a large value will affect the DGU overall efficiency. Hence, the proper design of these parameters consider power quality, operating conditions and transfer power DO.

IV. RESULTS

Multiple and diverse DO_{ref} are closely met, while the grid side power-quality standards are easily fulfilled with a very reduced converter current ripple; even in the presence of low switching frequencies and harmonic loads, with the best efficiency possible. In both design Case Studies, the performance of each DGU is seen by the network almost as an ideal harmonic free voltage source and prevents any harmonic related issue in the network caused by the operation of the DGUs. For this reason, the overall performance of the system and the obtained DE are very close in both case studies. However important differences should be pointed out.

Regarding the performance of $DG1$, an improvement of around 0.7% in the efficiency for comprehensive case could be noticed. Despite the relatively small improvement, notice that

there are significant differences among both DE, specially in the damping resistance. An interpretation is that in the comprehensive design, the damping is obtained from the grid resistances. This allows to improve the efficiency by decreasing R_{nf} while all the other DE are adjusted to meet the other DO_{ref} . For $DG2$, the isolated design

presents a difference in the output power P_{no} of around 30kW respect to the reference value, which results from non consideration of the interconnection grid. This difference is significantly improved in the comprehensive design. Additionally, most of the simulated design objectives in the comprehensive design are slightly better than in the isolated design. However a small decrease in the efficiency can be noticed, resulting from an increased R_{nf} value. In short, comprehensive design provides an improvement in the overall performance of $DG2$.

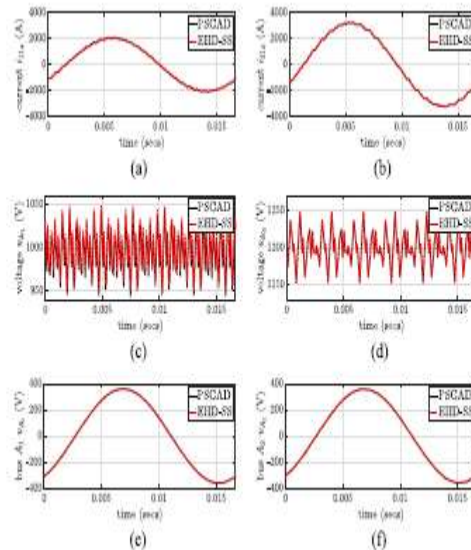


Fig. 4. Simulated waveforms for isolated design Case Study. (a) $DG1$ i_{11} converter current. (b) $DG2$ i_{21} converter current. (c) $DG1$ v_{1dc} voltage. (d) $DG2$ v_{2dc} voltage. (e) $DG1$ node 1A voltage. (f) $DG2$ node 2A voltage.

From the simulations shown in Fig. 4 it can be seen that both waveforms are practically overlapped. This validates the EHD model used to obtain the designable elements and the design approach proposed. The achieved power-quality indexes are excellent considering the high power capability and low switching frequency considered in the

design. When interconnected to the microgrid, each DGU behaves very close to an ideal harmonic free voltage source and their overall harmonic distortion impact over the microgrid is practically negligible. However, since each DGU was designed without considering all the elements interconnected to them, the obtained design is decoupled and the isolated operating conditions have to be verified when interconnected. From this point of view, a better design could be obtained if the complete system model is considered in the proposed design approach.

the harmonic distortion and its effects over multiple design objectives are explicitly considered. The design results of the presented case studies have shown a remarkable performance when both, the grid parameters are available and not available, offering an excellent power quality with the best efficiency possible in the presence of low switching frequencies. Compared with other design methodologies, this proposal offers an advanced performance, which rely on the comprehensive consideration of multiple design objectives.

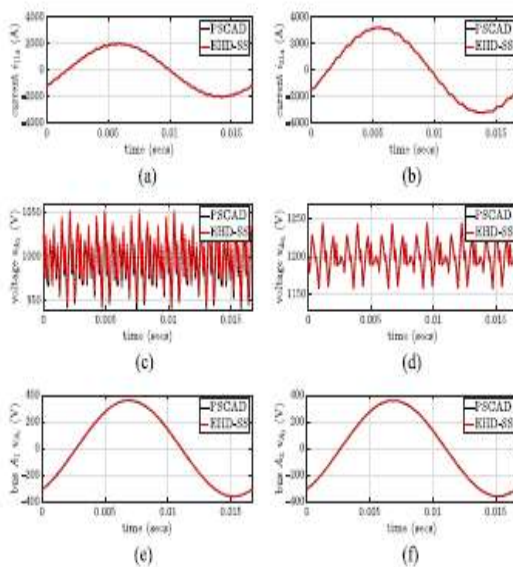


Fig.5. Simulated waveforms for comprehensive design Case Study. (a) DG1 i11 converter current. (b) DG2 i21 converter current. (c) DG1 v1dc voltage. (d) DG2 v2dc voltage. (e) DG1 node 1A voltage. (f) DG2 node 2A voltage.

V. CONCLUSION

This project has introduced a novel design methodology based on optimization and the extended harmonic domain (EHD) for interconnected distributed generation units (DGUs) in which

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